

## Nucleon-nucleon momentum correlation function for light nuclei

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Nucleon-nucleon momentum correlation function have been presented for nuclear reactions with neutron-rich or proton-rich projectiles using a nuclear transport theory, namely Isospin-Dependent Quantum Molecular Dynamics model. The relationship between the binding energy of projectiles and the strength of proton-neutron correlation function at small relative momentum has been explored, while proton-proton correlation function shows its sensitivity to the proton density distribution. Those results show that nucleon-nucleon correlation function is useful to reflect some features of the neutron- or proton-halo nuclei and therefore provide a potential tool for the studies of radioactive beam physics.

Both the enhancement of total reaction cross section of light nuclei induced reaction and the narrowing of the momentum distribution of the projectile-fragments care seen as the possible evidences of the halo nuclei [ 1, 2]. In addition, the weakening of the neutron-neutron momentum correlation function was also reported for the halo-nuclei induced system [ 3, 4]. Since the nucleon-nucleon momentum correlation function is related to the geometrical and kinematic information [ 5], i.e. spacial-time information, which gives the fact that the large spacial separation will give a weak correlation function. Therefore, the extended neutron or proton density distribution of halo nuclei could reveal weaker neutron-neutron or proton-proton correlation function.

In this work, we shall discuss some features of the nucleon-nucleon momentum correlation function in light nuclei induced reactions in the framework of quantum molecular dynamics (QMD) model [ 6]. Firstly, we would like to recall the momentum correlation function technique. Experimentally, the correlation function is defined as the ratio between the measured two-particle distribution and the product of the independent single-particle distributions,  $C(p_1, p_2) = \frac{dn^2/dp_1 dp_2}{dn/dp_1 dn/dp_2}$ , where  $d^2n/dp_1 dp_2$  represents the correlated two-particle distribution and  $dn/dp_1$  and  $dn/dp_2$  is the independent single-particle distribution of particle 1 and 2, respectively. While in the model calculation as we will present in this work, the standard Koonin-Pratt formalism [ 5] was used to construct the two-particle correlation function by convoluting the emission function  $g(\mathbf{p}, x)$ , i.e., the probability for emitting a particle with momentum  $\mathbf{p}$  from the space-time point  $x = (\mathbf{r}, t)$ , with the

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relative wave function of the two particles, i.e.,

$$C(\mathbf{P}, \mathbf{q}) = \frac{\int d^4x_1 d^4x_2 g(\mathbf{P}/2, x_1) g(\mathbf{P}/2, x_2) |\phi(\mathbf{q}, \mathbf{r})|^2}{\int d^4x_1 g(\mathbf{P}/2, x_1) \int d^4x_2 g(\mathbf{P}/2, x_2)}. \quad (1)$$

where  $\mathbf{P}(=\mathbf{p}_1 + \mathbf{p}_2)$  and  $\mathbf{q}(=\frac{1}{2}(\mathbf{p}_1 - \mathbf{p}_2))$  are the total and relative momenta of the particle pair respectively, and  $\phi(\mathbf{q}, \mathbf{r})$  is the relative two-particle wave function with  $\mathbf{r}$  being their relative position, i.e.,  $\mathbf{r} = (\mathbf{r}_2 - \mathbf{r}_1) - \frac{1}{2}(\mathbf{v}_1 + \mathbf{v}_2)(t_2 - t_1)$ .

Before we use Koonin-Pratt formalism to construct the correlation function, an event generator is necessary to get the phase space information of emission nucleons. In the present work, Isospin-dependent Quantum Molecular Dynamics (IDQMD) transport model has been used to give the particle production and their phase space information, and then construct a two-particle correlation function.

The Quantum Molecular Dynamics (QMD) approach is an n-body theory to describe heavy ion reactions from intermediate energy to 2 A GeV. It includes several important parts: the initialization of the target and the projectile nucleons, the propagation of nucleons in the effective potential, the collisions between the nucleons, the Pauli blocking effect and the numerical tests. A general review about QMD model can be found in [ 6]. The IDQMD model is based on QMD model affiliating the isospin factors, which includes the mean field, two-body nucleon-nucleon (NN) collisions and Pauli blocking etc [ 7, 8].

We simulate the reaction of  $^{11}\text{Li}$  fragments into  $^9\text{Li} + 2\text{n}$  at 28 MeV/u. The two-halo neutron correlation function and the core neutron-neutron correlation functions have been calculated. The right panel of Fig. 1 shows the experimental [ 3] and our calculation correlation functions for neutron-pair. The two halo neutrons in calculation are defined as the emitted neutrons in coincidence with  $^9\text{Li}$  core and the neutrons in the insert of the figure are the ones formed the core (i.e.,  $^9\text{Li}$ ) inside. The solid line is the calculated two-halo-neutrons correlation function and the dashed line in the insert is the core neutron-neutron correlation function. A corresponding carton can be found in the left panel of the figure. It shows clearly that the correlation function between the two halo neutrons reproduces the experimental data fairly well but the one between the core neutrons can not, which indicates that the source distributions of the halo neutrons and the neutrons inside the core are totally different, the former is much looser so that the two neutrons are easier to be separated, which is consistent with the small two neutron separation energy. This directly leads to the loose-bound neutron density distribution of  $^{11}\text{Li}$  which is the major reason for the abnormal larger total reaction cross section and the very narrow momentum distribution of the fragment  $^9\text{Li}$  [ 1, 2]. From the above discussion, it is clear that the correlation strength at small relative momentum ( $q$ ) is sensitive to the spatial extent of the emission source of neutrons, some information about the halo configuration could be learned from there.

Based on the above success to fit the data, we further made a prediction for the binding energy ( $E_b$ ) dependence of n-p correlation function strength for light isotopes. To this end, we select  $^{12}\text{C}$  as the target and  $\text{Li}$ ,  $\text{C}$  and  $\text{N}$ -isotopes as the projectile, respectively. The reactions are simulated at incident energy of 800 MeV/u and head-on collisions. The emitted nucleons which are taken into account in the correlation function calculation are all from the projectiles.

In order to make a quantitative comparison for the momentum correlation function from

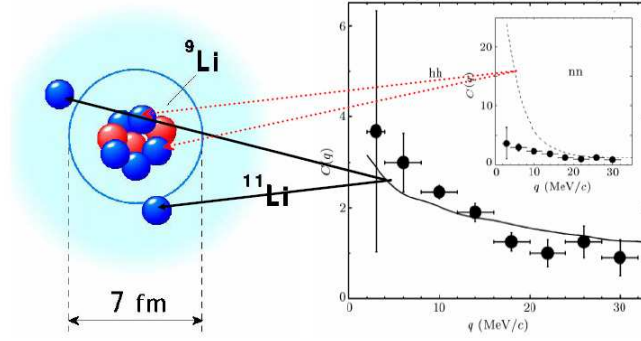


Figure 1. Left panel: a cartoon of the  $^{11}\text{Li}$ : core  $^9\text{Li}$  plus two halo neutrons; the solid and dashed lines point to the corresponding neutron-neutron correlation function of the right panel; Right panel: The solid circles with error bars are the two-halo correlation functions in the collision of  $^{11}\text{Li}$  fragmented into  $^9\text{Li} + 2n$  at 28 MeV/n [3]. The solid line is the calculated two-halo neutrons correlation function and the dashed line in the insert is the calculated two core neutrons correlation function.

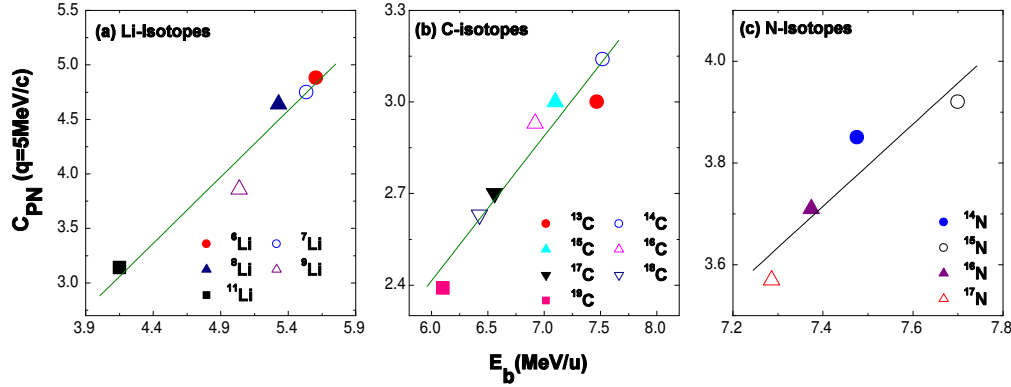


Figure 2. The relationship between the strength of proton-neutron correlation function  $C_{PN}$  at 5 MeV/c and the binding energy per nucleon of the projectiles for different isotopes:  $\text{Li}$  (a),  $\text{C}$  (b) and  $\text{N}$  (c).

different isotopes, the strength of n-p correlation function at very small relative momentum,  $q = 5 \text{ MeV/c}$ , has been extracted. Fig. 2 shows the behavior of the proton-neutron correlation function strength ( $C_{PN}$ ) as a function of binding energy of the projectiles. The fact that  $C_{PN}$  shows a rising with the increasing  $E_b$  reflects in some extent the larger  $C_{PN}$  corresponds to a more compact system, which is reasonable since the mean compactness between nucleons will change stronger with the increasing of the binding energy, therefore  $C_{PN}$  can more or less reveal the compactness of the nuclei.

After we discussed neutron-neutron, neutron-proton correlation functions, we shall investigate proton-proton correlation function. To this end, we selected some proton-rich nuclei, namely,  $^{27,28,29,30}\text{S}$ . Since  $^{27}\text{S}$  was predicted as two-proton halo nucleus, we would test the sensitivity of proton-proton correlation function to the proton density distribution. The left panel of Fig. 3 gives the density distribution of protons which were used as a different initial input in IDQMD calculation. The stars and the line show the proton density distribution with the usual Skyrme-Hartree-Fock calculation and the normal IDQMD initialization, respectively. In these cases, no special consideration for proton-halo density distribution. While the circles represent a halo-proton density distribution which is characterized by its long density tail. Now we compare the proton-proton correlation function ( $C_{PP}$ ) with either the normal density distribution (star) or the proton-halo density dis-

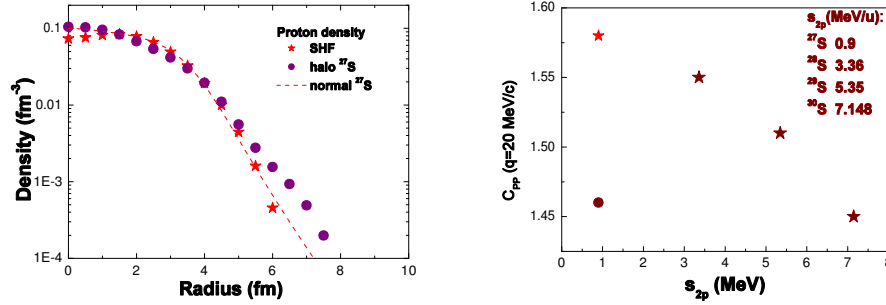


Figure 3. The left panel: the density distribution of protons as a different initial input in IDQMD. Right panel: p-p correlation function strength at 20 MeV/c as a function of the two-proton separation energy. See details in text.

tribution (circle). The right panel of Fig. 3 shows the p-p correlation function strength at 20 MeV/c as a function of the two-proton separation energy ( $s_{2p}$ ) of  $S$ -isotopes. If there is no special proton density distribution, the p-p correlation strength decreases with  $s_{2p}$  or the mass number of  $S$ -isotopes, which just illustrates that the system tends to be more loose when the mass number of  $S$ -isotopes increases. However,  $C_{PP}$  dramatically decreases when the proton-halo density is assumed in the QMD initialization (see circles in the figure). This kind of decreasing essentially reflects the extended density distribution of proton and incompact system of  $^{27}S$ .

In summary, nucleon-nucleon momentum correlation functions from light nuclei induced reactions have been systematically investigated and its sensitivity to the binding energy or separation energy of weakly-bound nuclei has been explored from the break-up reactions of nuclei in the framework of the IDQMD model. Firstly we gave a well-fitted halo neutron - halo neutron correlation function from the break-up of  $^{11}Li$  on  $C$  target. Based upon this achievement of the good fit, we explore the dependence of the proton-neutron correlation function ( $C_{PN}$ ) at small relative momentum with the binding energy for  $Li$ ,  $C$  and  $N$  isotopes. It was found that the correlation strength of  $C_{PN}$  at small relative momentum rises with the the binding energy. This changeable tendency of  $C_{PN}$  with  $E_b$  might be a potential good way to study the spatial structure of the light nuclei. In addition, the proton-proton correlation function shows a dramatic decrease for the proton-halo density distribution, which provides us another potential tool to diagnose proton halo nuclei.

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